Optical-Fiber Grating-Based Beamforming Network for Microwave Phased Arrays

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***Abstract*— A new photonic-based beamforming network that can realize a large number of simultaneous and independent beams in a wide-band phased-array antenna, and which eliminates optical beat-noise interference is presented. It is based on discrete and chirped Bragg-grating true-time delay elements and photodetector arrays at each beam port. This achieves a highly parallel delay-processing structure for signal equalization and eliminates the fundamental optical beat-noise limitation to the realization of large array sizes. Results show a very substantial reduction in the number of interconnects required of 98.4% for a 512-beam array and 99.2% for a 1024-beam array, in comparison to conventional beamforming techniques.**

***Index Terms*— Bragg gratings, microwave photonics, optical fiber interconnects, phase-array antennas.**

I. Introduction

PHASED-ARRAY antennas for high-performance radar and communication systems require highly efficient beamformers. Primary requirements include the capability of synthesizing multiple high-resolution beams and the ability to operate squint-free with high instantaneous bandwidth over a wide range of microwave frequencies. Photonics-based beamforming networks offer a number of advantages over electronic techniques, including the ability to provide true time delays for broad-band squint-free array performance, immunity to electromagnetic interference, as well as size, weight, and configuration properties which are attractive for the realization of large wide-band arrays [1], [2].

The ability to synthesize a large number of high-resolution and independent beams in a phased-array antenna raises particular problems. High-performance multifunction arrays requiring approximately 1000 independent beams have been impeded by the extreme complexity in realizing the beamforming networks. For example, in conventional approaches [3]–[6], an N-element array requires N optical-fiber interconnects for each beam direction for phase equalization. Hence, $M \times N$ interconnects are required for M beams, and for a large array when both M and N approach 1000, around 10^6 delay interconnects are needed, which is quite impractical.

Recently, wavelength multiplexing techniques have been investigated to increase the beamforming capabilities. The application of highly dispersive optical fibers for the delay function has been proposed [7]–[9]. The use of wavelength division multiplexing (WDM) in conjunction with array partitioning is effective for compressing the hardware requirements of photonic beamformers [10]–[12]. Nevertheless, these structures still require a substantial number of delay lines or are limited by the fundamental optical interference beat-noise effects of multiwavelength carriers which limits the array size which can be attained.

In this paper, we present a new photonic-based beamforming network which can realize a large number of simultaneous and independent beams in a wide-band phased-array antenna. This is based on a novel architecture which uses optical-fiber Bragg-grating delay elements and photodetector arrays. We exploit the wavelength selectivity of the gratings to realize a highly parallel delay-processing function inside the fibers and also to obtain efficient routing in the beamforming network. Hence, the fibers are no longer used as a simple interconnect, as with previous approaches, but instead perform the complex signal delay-processing equalization on a large number of array elements simultaneously within the fiber. Our topology uses multiple fiber Bragg gratings at different wavelengths distributed along the length of optical fibers and chirped gratings to realize the large range of true time delays required for phase equalization of multibeam phased arrays. This grating-based beamforming architecture results in a very significant reduction in the hardware complexity of the interconnect network, which to our knowledge is the lowest number reported, and opens the way to the realization large array sizes of the order of 500–1000 beams. In addition, we introduce a new photodetector array topology at each beam port, which enables the optical interference or beat notes to be eliminated in the beamforming network. This is important because for the first time it removes the fundamental beat-noise limitation to the realization of large array sizes.

The optical-fiber grating-based beamforming network and wavelength multiplexing technique is presented in Section II. Results are given in Section III for the number of interconnects required in the new architecture, the optimum partitioning and photodetector array size needed to eliminate optical beat-noise interference, and dynamic range improvement.

II. Beamformer Architecture and Description

Fig. 1 shows the architecture of the new grating-based wavelength multiplexed photonic-beamformer network. The delay-time profile which the beamforming network needs to

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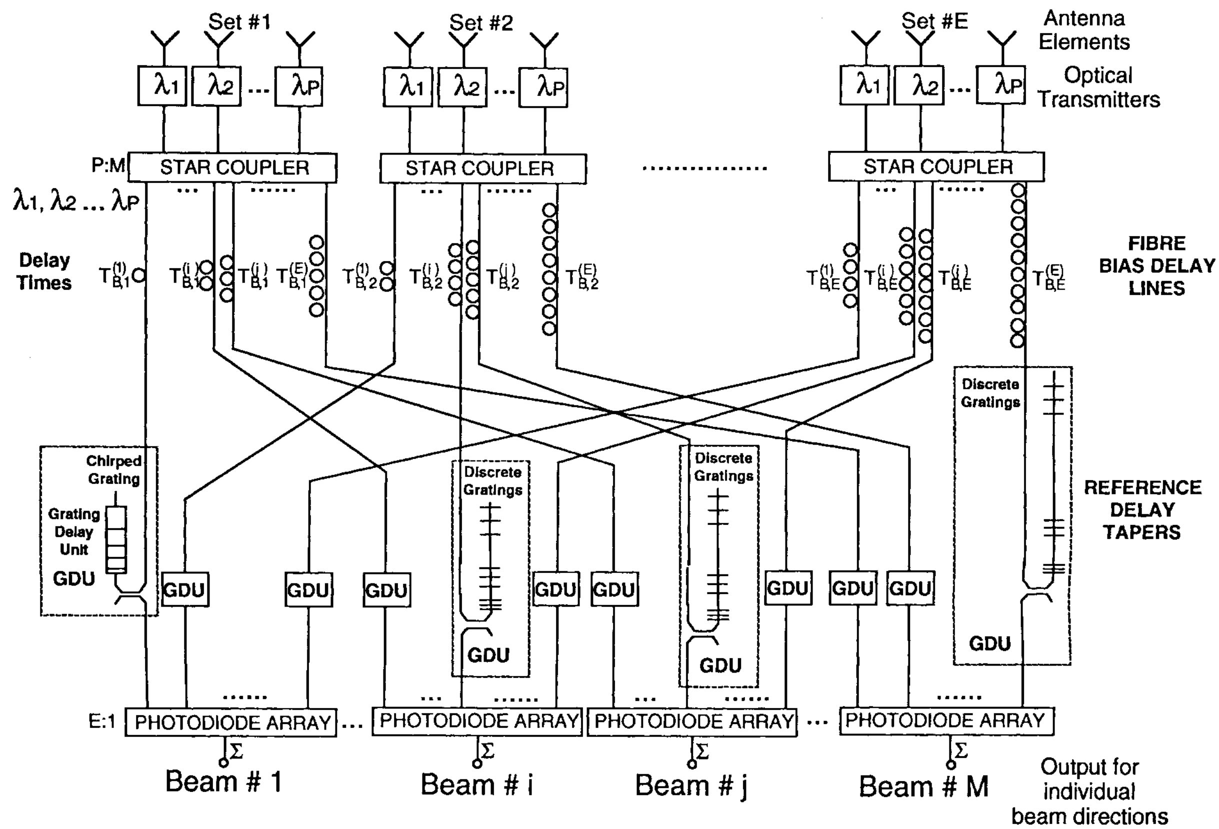

Fig. 1. Architecture of the optical-fiber grating-based wavelength multiplexed photonic-beamformer network for phased arrays.

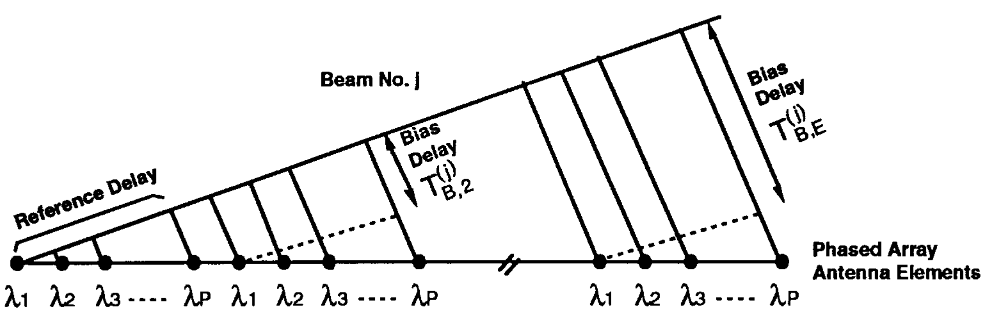

Fig. 2. Delay-time profile required for equalization and summation at the beam port.

provide for a single beam direction, for equalization, and to obtain constructive summation at the beam port is linear, as shown in Fig. 2. We use the partitioning concept and divide the array into E sets of P elements. This is displayed in Figs. 1 and 2. The antenna elements are assigned P equidistant wavelengths, which are the same for each set. This enables us to exploit the regularity characteristics of the delay profile inherent in Fig. 2. Hence, each set of P elements in Fig. 2 requires two components. One is a *linear delay taper* which is termed the Reference Delays, and is the *same for all sets*. The other is a Bias Delay which is the *same for all elements within a set*, but differs between sets.

The Bias Delays are obtained using normal fibers of appropriate lengths, which delays wavelengths in a given set. The Reference Delays require a linear time-wavelength characteristic. They are realized using periodically located discrete Bragg gratings or chirped gratings in fiber. Hence, different wavelengths are reflected off different points in the fiber and a delay-time taper is obtained. This argument also applies to all the other beam directions. P:M star couplers are used to split the optical signals of each set into M parts, so that M different beams can be independently synthesized to provide M-beam operation.

It should be noted that the beamforming network in Fig. 1 employs photodetector arrays at each beam port. As a result, for an N-element array, only P wavelengths are detected by each photodetector instead of detecting N wavelengths as reported in [10]–[12]. This is a significant feature of the proposed beamforming network, which can eliminate the important optical beat-noise problem, as described in Section II-B.

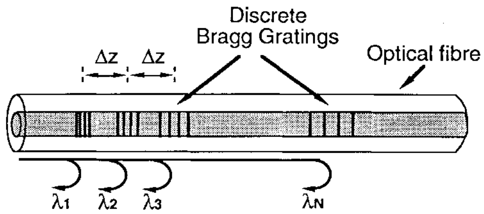

Fig. 3. Fiber Bragg-grating-based Reference Delay unit.

A. Grating-Based Reference Delay Units

The structure for obtaining the reference delay tapers is a key element in the network. The new delay unit for this function, which is based on fiber Bragg gratings, is shown in the network of Fig. 1. This uses the wavelength selectivity of the gratings so that the different wavelengths are reflected from different physical points along the fiber. Hence, the distance between the reflection points and the relative delays between the modulated optical carriers can be controlled to realize the entire linear true-time delay taper which is required for the reference delays in one single piece of fiber. The grating units in the beamforming network to give the different reference delays for the beam directions are shown in Fig. 1.

For multibeam arrays, a wide range of delay tapers are required. The large majority of the delay-time tapers are obtained using discrete Bragg gratings at equally spaced wavelengths that are periodically located in a fiber. We have previously demonstrated experimentally multiple-wavelength grating arrays in optical fiber [13]. A cascade of equidistant Bragg gratings of different center wavelengths written into a single optical fiber is shown in Fig. 3. Each wavelength is reflected at the grating whose center wavelength coincides with that wavelength; hence, the resultant time-delay characteristic is a linear taper with wavelength and realizes the Reference Delay requirement.

There is, however, a limit on the minimum attainable delay. This is set by the minimum distance allowed between two discrete gratings. Hence, discrete gratings cannot provide all the required delays since some beam directions (the nearly vertical ones) require shorter delays. For these cases, we employ chirped Bragg optical-fiber gratings to obtain these short delay tapers ($<$ 10 ps) in the beamforming network. Experimental measurements showing a linear delay taper obtained in a chirped grating [14] are displayed in Fig. 4.

B. Control of Optical Beat Noise

An important aspect of the wavelength multiplexed array operation is how to avoid optical interference or beat notes generated at the photodetectors. This is a central problem that has not previously been solved. In previous wavelength multiplexed beamforming networks [10]–[12], there are as many wavelengths needed as there are antenna elements, and all the optical carriers are incident on each photodetector. Because of the square-law nature of the photodetector, this generates beat notes. Ultimately, this limits the spacing between wavelengths which can be used so as to ensure that the difference beat-note RF frequency produced at the photodetector does not fall within the RF-signal bandwidth. Hence, for a given optical spectrum, this in turn limits the number of wavelengths which can be used. Thus, the array size is also limited.

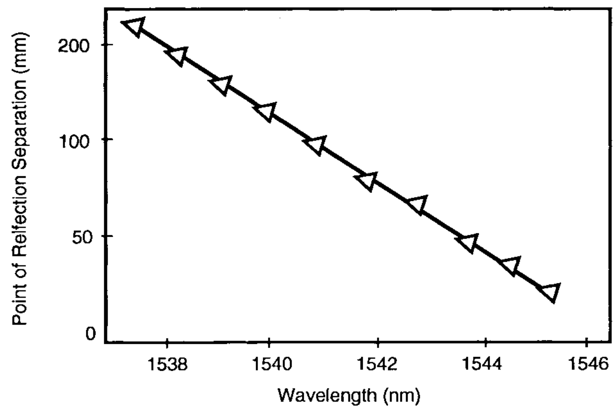

Fig. 4. Measured linear delay taper obtained in a chirped-fiber Bragg grating.

Our new topology in Fig. 1 overcomes the beat-noise problem by introducing a photodetector array at each beam port. In contrast to previous approaches where the number of wavelengths equals the number of array elements [10]–[12], it may be seen that this architecture only needs P wavelengths in an N-element array (where $P = N/E$ and $E > 1$). Also, each photodiode only receives P wavelengths. For example, if $E = 4$ sets, then for a 512-beam array, only 128 wavelengths are required in comparison to 512 wavelengths in previously reported architectures. It is also possible to use even fewer wavelengths if E is increased. This allows a larger spacing between the fewer wavelengths to be used in this topology. Hence, the beat-noise problem at the photodetectors can be effectively eliminated, since the beat notes can be made to fall out of band. The significance is it enables much larger arrays to be realized without being restricted by the fundamental beat-noise limitation.

C. Number of Wavelengths

This architecture requires fewer wavelengths than previous wavelength multiplexed-beamformer networks. Only $P = N/E$ wavelengths are required here for an N-element array, as compared to N wavelengths required in previous approaches [10]–[12]. The value of E corresponds to the partitioning and can be chosen by design. Moreover, this architecture simplifies the generation requirements of the multiple wavelengths. Hence, the wavelengths for all the E sets can be derived from a single multiple-wavelength master-comb optical source. This is because no photodetector receives the same multiple wavelength from two different sets, and hence, the possibility of optical coherence interference effects is eliminated.

D. Dynamic Range

Another important advantage of using a photodetector array is that the total optical-power incident on each photodetector is reduced by a factor of E times, in comparison to previous single photodetector networks. This leads to a reduction in photodiode nonlinearity and an extension in dynamic range. We have shown [15] that an increase in the optical power can increase the spurious-free dynamic range. However, ultimately

TABLE I

Number of Beams	Conventional No. of Interconnects	Previous WDM Network[12] No. of Interconnects	Proposed Architecture No. of Interconnects	Proposed Architecture Reduction wrt Conventional
256	65,536	4,096	2,048	96.9 %
512	262,144	9,216	4,096	98.4 %
1,024	1,048,576	20,480	8,192	99.2 %

it is the nonlinearity of the p-i-n photodetectors under high illumination [16] which introduces distortion products and fundamentally limits the dynamic range. In our architecture with the photodiode arrays, the received optical power per photodiode is reduced, and hence, a higher dynamic range can be attained. The price to pay for the above gains is an increased number of photodetectors, i.e., E photodetectors are used at each beam port instead of a single photodetector. However, this is not a problem because photodetector arrays are readily available [17], and this provides a fundamental advantage to the operation of the array.

III. Results

A. Number of Interconnects

The total number of interconnects required for this new beamforming network architecture can be seen from Fig 1. Each star coupler has M ports (i.e., one line for each individual beam direction) and there are E star couplers (i.e., one star coupler for each wavelength set in the partitioned array). Hence, the basic number of links needed in the beamformer is simply $E \cdot M$. Each of these links comprises an interconnect (which includes the fiber-bias delay line) from the star coupler to the grating delay unit and an interconnect from the grating unit to the photodiode array. Therefore, each link has two interconnects. Hence, the total number of interconnects required for an M beam array is

$$K = 2 \cdot E \cdot M = \frac{2 \cdot M \cdot N}{P}. \tag{1}$$

Comparing this to a conventional beamforming network which requires $M \cdot N$ optical interconnects, the reduction in optical interconnection hardware is given by

$$R = 1 - \frac{2}{P}. \tag{2}$$

Also, comparing this architecture to the previous partitioned WDM beamformer [12], which requires $2M \cdot \log_2(N)$ optical interconnects, the interconnct reduction is

$$R_{\mathrm{WDM}} = 1 - \frac{N}{P. \log_2(M)}. \tag{3}$$

For example, for a 512-beam array, if we partition the array elements into four wavelength sets then $E = 4$ and $P = 128$, and a large reduction in interconnection hardware of 98.4% is obtained as compared to a conventional beamforming network (BFN), and a reduction of 56% is obtained in comparison to the previous wavelength multiplexed beamformer [12]. Similarly, for a 1024-beam array the reduction is even larger, resulting

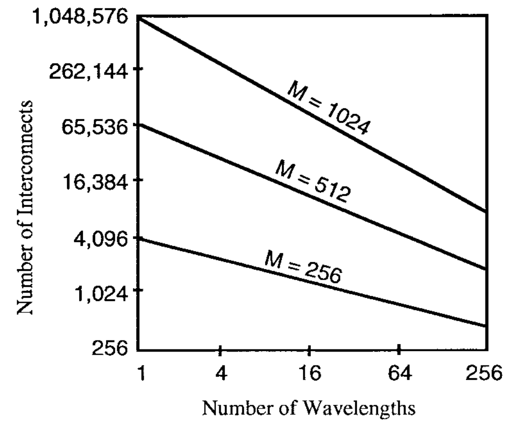

Fig. 5. Required number of interconnects versus number of wavelengths for a given number of beams M.

in a 99.2% reduction compared to a conventional BFN, and 60% in comparison to the previous wavelength multiplexed network [12]. Table I shows examples of the savings possible with this new architecture.

The reason that this new beamforming network can achieve such a significant reduction is because it introduces a wavelength routing structure with grating-based wavelength-dependent delays, which provides the numerous delay functions needed for phase equalization of signals *in parallel* within each fiber. Hence, this dramatically reduces the complexity of the beamforming network and opens the way toward making large arrays realizable.

It may be noted that this network is quite versatile in that it can accommodate a range of wavelength numbers. Thus, if the number of wavelengths is limited, then the number of E sets can be increased so that the number of wavelengths required in the beamforming network is reduced. This is useful if a limited number of wavelengths is available. However, the tradeoff is that an increase in the number of interconnects results. Fig. 5 shows how the number of interconnects depends on the number of wavelengths used for different numbers of beams. The hardware reduction is particularly advantageous for a large number of beams (which is the most difficult case), and for example, for $M = 1024$ beams, if a limited number of 128 wavelengths are used ($E = 8$ partitioning), there is still a 98.4% reduction in the number of interconnects compared to conventional architectures.

B. Elimination of Optical Beat-Note Interference

This beamforming network topology eliminates the beat-noise problem prevalent in previous wavelength multiplexed approaches by using photodiode arrays at each beam port, which enables a larger wavelength spacing to be used. If the phased array has M beams and is required to operate over a microwave range Δf, and the optical spectrum available for the beamforming network and delay units spans a wavelength range of $\Delta\lambda$ centered on a wavelength λ, then the required partitioning in the beamforming network of Fig. 1 to eliminate optical beat notes falling within the signal bandwidth is given by

$$E = \frac{2M\Delta f \lambda^2}{c\Delta\lambda} \tag{4}$$

where E is the closest integer. Hence, any number of beams and phased-array operating frequency range can be handled without beat-note problems by partitioning according to (4).

C. Dynamic Range Improvement of the Phased Array

The use of photodetector arrays in the beamforming architecture reduces the photodiode nonlinearity and can extend the dynamic range. Attempts to increase the spurious-free dynamic range by increasing the power budget of the photonic beamforming network are often thwarted by the nonlinearities due to the high optical-power levels incident on the photodiodes. In the overall third-order intercept point of the system given by [18]

$$P_{\mathrm{TOI,tot}} = \left(\sum_k \frac{1}{P_{\mathrm{TOI},k}}\right)^{-1} \tag{5}$$

where $P_{\mathrm{TOI},k}$ is the third-order intercept at the output due to the individual cascaded two-ports which comprise the system, the main contributions are nonlinearities at the transmitter and receiver. Efficient linearization schemes can be employed at the transmitter [19]. However, this still leaves the basic photodetector nonlinearity at the receiver as a dominant effect which ultimately limits the dynamic range. This fundamental limitation is reduced in the architecture given in Fig. 1 because it employs a photodetector array at each beam port. Hence, the received optical power per photodiode is reduced by a factor of E times. This means that for a given system's operating power level, considerably less distortion will be generated at the receiver. Alternatively, this permits higher system operating power levels to be used before significant nonlinear distortion is produced, resulting in a higher dynamic range.

IV. Conclusion

A new photonic-based beamforming network which can realize a large number of simultaneous and independent beams in a wide-band phased-array antenna, and which eliminates optical beat-noise interference has been presented. It is based on fiber Bragg-grating true time-delay elements and photodetector arrays at each beam port. The topology uses multiple fiber gratings at different wavelengths located along the length of fibers and chirped gratings, which can be individually addressed via the source wavelength to provide the large range of time delays required for phase equalization of the multibeam phased array. This exploits the wavelength selectivity of gratings to realize a highly parallel delay-processing function which perform the complex signal delay-processing equalization on a large number of array elements simultaneously within the fiber. The topology results in a very substantial reduction in the number of interconnects required (98.4% for a 512 beam array, and 99.2% for a 1024-beam array) in comparison to conventional beamforming techniques. This is the lowest number of interconnects reported to date.

An important feature of this beamforming network is that it eliminates the optical interference or beat notes generated at the photodetectors. This is achieved through the introduction of photodiode arrays at each beam port, which enables an increased wavelength separation to be used so beat notes fall out of band. This is significant because for the first time it removes the fundamental beat-noise limitation to the realization of large array sizes. Moreover, this beamforming network requires fewer wavelengths which are more easily generated than previous wavelength multiplexed-beamformer networks and it enables the dynamic range to be increased because the photodiode nonlinearity limitation is reduced. The beamforming architecture provides the capability for realizing large arrays and has application to high-resolution multiple-beam phased arrays with wide-band microwave operation.

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